

BOOSTER BEAM LOSS  
DUE TO BEAM-RESIDUAL GAS CHARGE EXCHANGE

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## INTRODUCTION

The vacuum requirement of the Booster ring is mainly imposed by the interaction between the heavy ions and the residual gas molecules. Among the primary interactions, the cross sections of charge exchange (electron capture and strip) are several orders of magnitude higher than those of nuclear scattering and of multiple Coulomb scattering. The secondary interactions such as the secondary ion induced desorption, the bunch induced multipactorizing and the beam neutralization are more relevant to storage rings than to the accelerators. The dominant beam loss process in the Booster, therefore, will be the charge exchange between the beam and the residual gas molecules.

The Booster vacuum requirement based on charge exchange was analyzed several years ago by G.R. Young (see RHIC-PG-16, December 8, 1983). In his note, a linac after Tandem was assumed, and there were only a few cross sectional data existed for extrapolation to Booster ranges. Since then, more abundant data are available, which make better estimate of the Booster vacuum requirement possible.

In this technical note, the best empirical formulae for charge exchange cross sections are selected. The beam losses due to charge exchanges are calculated for gold (Au+33) and iodine (I+29). At the designed vacuum of  $3 \times 10^{-11}$  Torr (90% H<sub>2</sub> and 10% N<sub>2</sub>/CO), the beam loss amounts to less than one percent for gold.

## ELECTRON CAPTURE

The capture cross section can be expressed as

$$\sigma_{\text{capt}} \propto \beta^{\ell} * q^m * Zt^n$$

here  $\beta = v/c$ , q the projectile charge state, Zt the atomic number of the residual gas. The values of  $\ell$  vary between -6 and -12, of m >= 2, and of n <= 1. The capture cross section is significant at low energy and drops off rapidly during the acceleration cycle.

Among the different experimental and theoretic works on predicting capture cross sections, the scaling rule proposed by A.S. Schlachter, et.al (Phys. Rev. A27, 3372(1983)) gives the best fitting to the existing data and is used in this note. A detailed comparison of several empirical formulae with the experimental data is given in Appendix.

## ELECTRON LOSS(STRIPE)

The loss cross sections can be expressed as

$$\delta_{\text{str}} \propto \beta^{\ell} * q^m * Zt^n * Zp^r$$

with  $Z_p$  the atomic number of the projectile (heavy ions).

Calculations of the loss cross sections based on plane wave Born approximation and inner shell ionizations are available in the literatures. At Booster energy range ( $\beta > 0.05$ ), the loss cross sections decrease slowly with increasing  $\beta$  (with  $\ell$  between -1 and -2) and become the dominant beam loss process at higher energy. A modified empirical formula based on Bohr-Lindhard formulae (H.D. Betz, Rev. MoD. Phys. 44, 465(1972)) is used in our calculation.

$$\delta_{\text{str}} = 9 \times 10^{-19} * q^{-3} * \beta^{-1} * Zt * Zp^2 \quad (1)$$

The results are within a factor  $\sqrt{2}$  of the existing data. Detailed comparison among different empirical formulae and the existing data is also given in Appendix.

#### BEAM LOSS DUE TO CHARGE EXCHANGE

The beam loss due to charge exchange can be expressed by

$$-dN/N = \delta_t * n * dl \quad \text{or} \quad N/N_0 = \exp(-\int_0^t \delta_t * n * dl)$$

with  $-dN/N$  the fraction of the beam loss after travelling  $dl$   
 $\delta_t$  the sum of the capture and the strip cross sections  
 $n$  the gas density,  $= 3.3 \times 10^{16} * P$   
 $P$  pressure in Torr  
 $dl$  the distance travelled,  $= \beta * c * dt$

We know the charge states of the heavy ions from Tandem. The composition of the residual gas at certain pressures can be specified. Now we need  $\beta(t)$  or  $E(t)$  to derive the cross sections.

Based on the acceleration schemes in the design manual, we have the equation for the energy gain for the ions as

$$dE(t) = V(t) * \sin \theta * q / A * \beta(t) * c / \phi * dt$$

with  $V(t)$  the peak RF voltage  
 $\theta$  the stable phase angle (between  $17^\circ$  and  $22^\circ$ )  
 $A$  the atomic mass of the heavy ions  
 $\phi$  the circumference of the ring.

The  $E(t)$  and  $\beta(t)$  can be calculated by integrating  $dE(t)$  over  $t$  after injection and capture, then  $\delta_t$  and  $N/N_0$  can be derived. This integration will be rather complicated and messy, since  $V$ ,  $\beta$ ,  $E$  and  $\delta_t$  are functions of one another through the acceleration cycle. Instead, we have opted to calculate them through consecutive intervals with small increment in  $t$ , for example with  $dt = 1 \text{ msec}$ .

Two cases are analyzed, Au +33 at 0.92 MeV/A (latest energy and charge state available from Tandem) and I+29 at 1.65 MeV/A.

The peak RF voltages  $V(t)$  are

$$\begin{array}{ll} \text{Au+33} & V = 0.88 + 0.69 * t \text{ KV for } t \leq 20 \text{ ms and } 14.6 \text{ KV for } t > 20 \text{ ms} \\ \text{I+29} & V = 0.64 + 0.64 * t \text{ KV for } t \leq 20 \text{ ms and } 13.5 \text{ KV for } t > 20 \text{ ms} \end{array}$$

An average stable phase angle of  $20^\circ$  is assumed.

The following vacuum conditions are specified:

$$\begin{array}{ll} 3 \times 10^{-11} \text{ Torr} & - 90\% \text{ H}_2 \text{ and } 10\% \text{ CO (designed vacuum)} \\ 1 \times 10^{-10} \text{ Torr} & - 50\% \text{ H}_2 \text{ and } 50\% \text{ N}_2 \text{ (due to small leaks)} \\ 3 \times 10^{-10} \text{ Torr} & - 90\% \text{ N}_2 \text{ and } 10\% \text{ H}_2 \text{ (due to large leaks).} \end{array}$$

The calculation for gold over the first 50 ms is given in Table I. The "LOSS" and "SUM-L" are the instant and accumulated beam loss(in percent). For a mixture of gases, the cross section will be the fractional summing of the individual ones (i.e. CAPT<sub>I</sub> = 0.9 \* CAPT-H + 0.1 \*CAPT-N).

The capture and loss(strip) cross sections for N<sub>2</sub>/CO and for H<sub>2</sub> are plotted versus  $\beta$  in Figures 1 & 2 for Au and I respectively. On figures 3 and 4, the  $\beta$  and the accumulated beam loss at these three vacuum conditions are plotted against  $t$  for the first 500 msec. At the designed vacuum of  $3 \times 10^{-11}$  Torr, the beam loss for all the heavy ions will be less than one percent. This agrees with Young's estimate.

At  $3 \times 10^{-10}$  Torr, upto 30 % of gold would be lost while less than 10% of iodine would not survive. This results are higher than those of Young's, and are understandable, since we assumed 90% nitrogen which would be the worst case.

## CONCLUSION

The Booster ring vacuum requirement is analyzed based on the charge exchange between beam and the residual gas molecules. The cross sections are estimated rather conservatively. The calculated beam loss is, therefore the upper bound. At the designed vacuum of  $3 \times 10^{-11}$  Torr (90% hydrogen), the beam loss for the heaviest ions such as gold will be negligibly small.

The beam loss during the multiturn injection and before rf capture are not included here. It should be small because of the short period (< 1ms). Slower rf capture and acceleration will lead to slightly higher loss rates.

## APPENDIX. CHARGE EXCHANGE CROSS SECTIONS

The electron capture and loss cross sections considered here should include both single and multiple electron capture and loss. However multiple cross sections are usually less than 20% of the single cross section (H. Knudson et.al. Phys. Rev. A23, 597(1981) and W.G. Graham et.al. Phys. Rev. A30, 722(1984)) and can be

neglected for practical purpose.

The existing theoretical works and the experimental data cover a wide range of heavy ions, charge states, energy ranges and target gases. We will try to select some empirical or semi-empirical formulae, which give best fitting to the existing data.

#### CAPTURE CROSS SECTION

In general, the single electron capture cross sections are characterized by the ratio  $v/v_0$ , with  $v_0$  the Bohr velocity ( $= 2.2 \times 10^8$  cm/s). In the intermediate- and high-energy range ( $v/v_0 > 1$ ), the cross sections generally scale as  $v^{-\ell}$  with  $\ell$  approaching 11 at high . The cross sections also scale with  $q^m$  and  $Zt^n$  with  $m > 2$  and  $n > 1$ .

Most of the theoretical works center on that of the Bohr-Lindhard's equation of

$$\delta_{\text{capt}} = \pi * a_0^2 * Zt^{1/3} * q^2 * (v_0/v)^6$$

with  $a_0$  the Bohr radius ( $= 5.3 \times 10^{-9}$  cm). Three empirical formulae as well as the "Scaling Rule" discussed below are selected to calculate the capture cross sections. They are compared with the experimental data in Table II.

Note that for diatomic gas, the predicted cross sections should be twice of those given by these equations.

#### SCALING RULE FOR CAPTURE CROSS SECTION

A universal scaling rule proposed by A.S. Schlachter et.al. (Phys. Rev. A27, 3372(1983) permits prediction of cross sections for a wide range of fast, highly charged heavy ions in different gas targets.

It uses the generalized reduced coordinates

$$\delta' = \delta_{\text{capt}} * Zt^{1.8} / q^{0.5} \quad \text{and} \quad E' = E / (Zt^{1.25} * q^{0.7})$$

then the capture cross sections  $\delta'$  can be calculated thru  $\delta'$  by

$$\delta' = \frac{1.1 \times 10^{-8} [1 - \exp(-0.037 * E'^{2.2})] [1 - \exp(2.44 \times 10^{-5} * E'^{2.6})]}{E'^{4.8}}$$

As can be seen in Table II, it fits well to over 90% of the data (within a factor of two) with the exception of those for light ions and from ref. D.

#### LOSS(STRIK) CROSS SECTION

The most recent theoretical investigation of the strip cross sections are reported by G.H. Gillespie (Nucl. Instr. Methods, 176, 611(1980) using sum rules and by I.S. Dmitriev (Nucl. Instr.

Methods, 164, 329(1979) using a semiempirical formula. In their works, the Bethe inelastic scattering cross sections for individual initial and final states were summed up. The formulae show a strong  $\beta^{-2}$  dependent and can be expressed as

$$\delta_{\text{str}} = 8\pi * \alpha^2 * \alpha'^2 * [I] / \beta^2$$

with  $\alpha$  the fine structure constant ( $= 0.0073$ ), and  $I$  the collision strength.

These calculations include both the excitation (which does not necessarily lead to electron loss) and the ionization. They, therefore, usually overestimate the actual loss cross sections, sometimes by more than one order of magnitude. The formulae are better suited for low  $q$ , low  $Z$  ions with  $\beta > 0.1$ .

Several other semiempirical formulae obtained by fitting the experimental data to the model described in H.D. Betz. They have the following general form:

$$\delta_{\text{str}} = A * \beta^{\ell} * q^m * Zt^n * Zp^r$$

with  $\ell$  between -1 to -1.5,  $m$  -3 to -4,  $n < 2$  and  $r \geq 2$  to 2.5. We have selected and modified that of J. Alonso and H. Gould (Phys. Rev. A26, 1134(1982)) for our calculation, which gives the best fit to the existing data.

Comparison among the different formulae is given in Table III. With the exception of those with "\*\*\*\*", the formula of HCH gives within a factor of two to the experimental data. Most of those with "\*\*\*\*" are again from ref. D. The calculated values from sum rules are also listed under "X-expt" from ref. G.

Note again for the diatomic gas, the calculated values should be multiplied by 2 to take into account the molecular effect.

TABLE I. CHARGE EXCHANGE CROSS SECTIONS AND BEAM LOSS IN BOOSTER  
 Au(+33,  $E_{inj}$  = 0.92 MeV/A)

$$\beta = [1 - (1 + E/931.5)^{-2}]^{1/2}$$

$$W = \beta C/201.6 = 1490 \times \beta \text{ turns/ms}$$

$$V = 0.8 + 0.7 \times t \text{ KV} \quad (t < 20 \text{ ms}) \quad \text{or} = 14.6 \text{ KV}$$

$$DE = W \cdot V \cdot \sin(2\pi) \cdot 33/197 = (0.068 + 0.06 \cdot t) \cdot \beta \text{ MeV/ms for } t < 20 \text{ ms}$$

$$\text{or } 1.246 \cdot \beta \text{ MeV/ms for } t > 20 \text{ ms}$$

$$E' = 1000 \cdot E / (Zt^2 \cdot 1.25 \cdot 0.7) = 86.5 \cdot E(H) = 7.6 \cdot E(CO)$$

$$CAP1 = 1.1e-8 \cdot [1 - \exp(-2.44e-5 \cdot E'^2 \cdot 2.6)] / E'^4 \cdot 8$$

$$CAP-H = 2 \cdot CAP1 \cdot H^2 \cdot Q^2 \cdot 0.5 / Zt^2 \cdot 1.8 = 11.4 \cdot CAP1 \cdot H$$

$$CAP-CO = 2 \cdot CAP1 \cdot CO^2 \cdot Q^2 \cdot 0.5 / Zt^2 \cdot 1.8 = 0.346 \cdot CAP1 \cdot CO$$

$$CAP1(90H) = CAP-H + CAP-CO \cdot 0.1$$

$$CAP2(50H) = CAP-H + CAP-CO \cdot 0.5$$

$$CAP3(10H) = CAP-H + CAP-CO \cdot 0.9$$

$$TOTAL = CAP1 + STR1 \text{ or } CAP2 + STR2 \text{ or } CAP3 + STR3$$

$$LOSS = (-1/N) (dN/dt) = TOTAL \cdot 1/n \quad n = 3.3 \cdot 10^{16} \cdot P(\text{Torr})$$

$$= 9.9 \cdot 10^{23} \cdot \beta \cdot P \cdot TOTAL / \text{ms}$$

$$1 = \beta \cdot C \cdot dt$$

$$STR = 9e-19 \cdot Q^{-3} \cdot \beta^{-1} \cdot Zt \cdot Z^2 \cdot t^2$$

$$STR-H = 2 \cdot STR = 3.1e-19 / \beta$$

$$STR-CO = 2 \cdot STR = 2.2e-18 / \beta$$

$$STR1(90H) = 0.9 \cdot STR-H + 0.1 \cdot STR-CO$$

$$STR2(50H) = 0.5 \cdot STR-H + 0.5 \cdot STR-CO$$

$$STR3(10H) = 0.1 \cdot STR-H + 0.9 \cdot STR-CO$$

LOSS = percent of beam loss over dt

SUM = cumulative beam loss from 0 to t

t (ms)	$\beta$	E	dE	I-SR	Capture Cross Section			Strip Cross Section			Pressure in Torr														
					E' H	E' CO	CAP-H	CAP-CO	CAP1	CAP2	CAP3	STR-H	STR-CO	STR1	STR2	STR3	LOSS	SUM	LOSS	SUM					
0	0.04	0.9	79.6	9.9	0.04	0.9	0.00	80.7	7.0	9E-17	1E-15	2E-16	7E-16	1E-15	7E-18	5E-17	1E-17	3E-17	5E-17	0.02	0.02	0.31	0.31	1.61	1.61
1	0.04	0.9	0.00	80.7	7.0	8E-17	1E-15	2E-16	7E-16	1E-15	7E-18	5E-17	1E-17	3E-17	4E-17	0.02	0.05	0.31	0.63	1.59	3.18				
2	0.04	0.9	0.01	81.7	7.1	8E-17	1E-15	2E-16	7E-16	1E-15	7E-18	5E-17	1E-17	3E-17	4E-17	0.02	0.08	0.30	0.93	1.57	4.70				
4	0.04	0.9	0.01	82.7	7.2	8E-17	1E-15	2E-16	6E-16	1E-15	7E-18	5E-17	1E-17	3E-17	4E-17	0.02	0.11	0.30	1.23	1.54	6.18				
5	0.04	0.9	0.01	84.7	7.4	7E-17	1E-15	2E-16	6E-16	1E-15	7E-18	5E-17	1E-17	3E-17	4E-17	0.02	0.13	0.29	1.52	1.50	7.59				
6	0.04	0.9	0.01	86.7	7.5	7E-17	1E-15	2E-16	6E-16	1E-15	7E-18	5E-17	1E-17	3E-17	4E-17	0.02	0.16	0.28	1.81	1.46	8.94				
7	0.04	0.9	0.02	88.7	7.7	6E-17	1E-15	2E-16	6E-16	1E-15	7E-18	5E-17	1E-17	3E-17	4E-17	0.02	0.18	0.27	2.08	1.41	10.2				
8	0.04	0.9	0.02	90.7	7.9	6E-17	1E-15	2E-16	5E-16	9E-16	7E-18	5E-17	1E-17	3E-17	4E-17	0.02	0.21	0.26	2.34	1.36	11.4				
9	0.04	0.9	0.02	92.8	8.1	5E-17	1E-15	1E-16	5E-16	9E-16	6E-18	5E-17	1E-17	3E-17	4E-17	0.02	0.23	0.25	2.59	1.31	12.6				
10	0.04	0.9	0.03	95.8	8.3	4E-17	9E-16	1E-16	5E-16	8E-16	6E-18	5E-17	1E-17	3E-17	4E-17	0.02	0.25	0.24	2.82	1.25	13.7				
11	0.04	0.9	0.03	98.8	8.6	4E-17	9E-16	1E-16	4E-16	8E-16	6E-18	4E-17	1E-17	3E-17	4E-17	0.01	0.27	0.23	3.05	1.19	14.7				
12	0.04	0.05	1.1	0.03	101.8	8.9	3E-17	8E-16	1E-16	4E-16	7E-16	6E-18	4E-17	1E-17	2E-17	4E-17	0.01	0.29	0.21	3.26	1.13	15.7			
13	0.05	0.05	1.2	0.04	105.9	9.2	3E-17	7E-16	1E-16	4E-16	7E-16	6E-18	4E-17	1E-17	2E-17	4E-17	0.01	0.30	0.20	3.46	1.07	16.6			
14	0.05	0.05	1.2	0.04	109.9	9.6	2E-17	7E-16	9E-17	4E-16	6E-16	6E-18	4E-17	1E-17	2E-17	4E-17	0.01	0.32	0.19	3.65	1.01	17.4			
15	0.05	0.05	1.3	0.05	114.10	10.	2E-17	6E-16	8E-17	3E-16	6E-16	6E-18	4E-17	9E-18	2E-17	4E-17	0.01	0.33	0.18	3.82	0.95	18.2			
16	0.05	0.05	1.3	0.05	118.10	10.	2E-17	6E-16	7E-17	3E-16	5E-16	6E-18	4E-17	9E-18	2E-17	4E-17	0.01	0.35	0.17	3.99	0.89	18.9			
17	0.05	0.05	1.4	0.05	123.10	10.	1E-17	5E-16	7E-17	3E-16	5E-16	6E-18	4E-17	9E-18	2E-17	4E-17	0.01	0.36	0.16	4.14	0.83	19.6			
18	0.05	0.05	1.4	0.06	129.11	11.	1E-17	5E-16	6E-17	2E-16	4E-16	5E-18	4E-17	8E-18	2E-17	4E-17	0.01	0.37	0.14	4.29	0.78	20.2			
19	0.05	0.05	1.5	0.06	135.11	11.	9E-18	4E-16	5E-17	2E-16	4E-16	5E-18	4E-17	9E-18	2E-17	3E-17	0.01	0.38	0.13	4.42	0.73	20.8			
20	0.05	0.05	1.6	0.07	141.12	12.	8E-18	4E-16	5E-17	2E-16	4E-16	5E-18	4E-17	8E-18	2E-17	3E-17	0.00	0.39	0.12	4.54	0.68	21.4			
21	0.05	0.05	1.7	0.07	147.13	13.	6E-18	4E-16	4E-17	2E-16	3E-16	5E-18	4E-17	8E-18	2E-17	3E-17	0.00	0.40	0.12	4.66	0.63	21.9			
22	0.06	0.06	1.7	0.07	154.13	13.	5E-18	3E-16	4E-17	2E-16	3E-16	5E-18	4E-17	8E-18	2E-17	3E-17	0.00	0.41	0.11	4.77	0.59	22.3			
23	0.06	0.06	1.8	0.07	161.14	14.	4E-18	3E-16	3E-17	2E-16	3E-16	5E-18	3E-17	8E-18	2E-17	3E-17	0.00	0.41	0.10	4.87	0.55	22.8			
24	0.06	0.06	1.9	0.07	167.14	14.	3E-18	3E-16	3E-17	1E-16	2E-16	5E-18	3E-17	8E-18	2E-17	3E-17	0.00	0.42	0.09	4.96	0.51	23.2			
25	0.06	0.06	2.0	0.08	174.15	15.	3E-18	2E-16	3E-17	1E-16	2E-16	5E-18	3E-17	8E-18	2E-17	3E-17	0.00	0.43	0.09	5.05	0.48	23.5			
26	0.06	0.06	2.1	0.08	182.15	15.	2E-18	2E-16	2E-17	1E-16	2E-16	5E-18	3E-17	7E-18	2E-17	3E-17	0.00	0.43	0.08	5.13	0.45	23.9			
27	0.06	0.06	2.1	0.08	189.16	16.	2E-18	2E-16	2E-17	1E-16	2E-16	5E-18	3E-17	7E-18	2E-17	3E-17	0.00	0.44	0.08	5.21	0.43	24.2			
28	0.06	0.06	2.2	0.08	196.17	17.	2E-18	2E-16	2E-17	9E-17	2E-16	4E-18	3E-17	7E-18	2E-17	3E-17	0.00	0.44	0.07	5.28	0.40	24.5			
29	0.06	0.07	2.3	0.08	204.17	17.	1E-18	2E-16	2E-17	9E-17	2E-16	4E-18	3E-17	7E-18	2E-17	3E-17	0.00	0.45	0.07	5.35	0.38	24.8			
30	0.07	0.07	2.4	0.08	211.18	18.	1E-18	2E-16	2E-17	8E-17	1E-16	4E-18	3E-17	7E-18	2E-17	3E-17	0.00	0.45	0.06	5.42	0.36	25.1			
31	0.07	0.07	2.5	0.09	219.19	19.	9E-19	1E-16	2E-17	7E-17	1E-16	4E-18	3E-17	7E-18	2E-17	3E-17	0.00	0.46	0.06	5.48	0.34	25.3			
32	0.07	0.07	2.6	0.09	227.19	19.	7E-19	1E-16	1E-17	7E-17	1E-16	4E-18	3E-17	7E-18	2E-17	3E-17	0.00	0.46	0.05	5.54	0.32	25.6			
33	0.07	0.07	2.7	0.09	235.20	20.	6E-19	1E-16	1E-17	6E-17	1E-16	4E-18	3E-17	7E-18	2E-17	3E-17	0.00	0.47	0.05	5.59	0.31	25.8			
34	0.07	0.07	2.8	0.09	243.21	21.	5E-19	1E-16	1E-17	5E-17	1E-16	4E-18	3E-17	6E-18	2E-17	3E-17	0.00	0.47	0.05	5.64	0.29	26.0			
35	0.07	0.07	2.9	0.09	252.22	22.	5E-19	1E-16	1E-17	5E-17	1E-16	4E-18	3E-17	6E-18	2E-17	3E-17	0.00	0.48	0.05	5.70	0.28	26.3			
36	0.07	0.08	3.0	0.09	260.22	22.	4E-19	1E-16	1E-17	5E-17	9E-17	4E-18	3E-17	6E-18	2E-17	3E-17	0.00	0.48	0.05	5.74	0.26	26.4			
37	0.08	0.08	3.1	0.09	269.23	23.	3E-19	9E-17	9E-18	5E-17	8E-17	4E-18	3E-17	6E-18	2E-17	3E-17	0.00	0.48	0.04	5.79	0.25	26.6			
38	0.08	0.08	3.2	0.10	278.24	24.	3E-19	8E-17	9E-18	4E-17	8E-17	4E-18	3E-17	6E-18	2E-17	3E-17	0.00	0.49	0.04	5.83	0.24	26.8			
39	0.08	0.08	3.3	0.10	287.25	25.	2E-19	8E-17	8E-18	4E-17	7E-17	4E-18	3E-17	6E-18	1E-17	2E-17	0.00	0.49	0.04	5.88	0.23	27.0			
40	0.08	0.08	3.4	0.10	296.26	26.	2E-19	7E-17	7E-18	4E-17	7E-17	4E-18	3E-17	6E-18	1E-17	2E-17	0.00	0.49	0.04	5.92	0.22	27.2			
41	0.08	0.08	3.5	0.10	305.26	26.	2E-19	7E-17	7E-18	4E-17	6E-17	4E-18	3E-17	6E-18											

TABLE II

COMPARISON OF THE ELECTRON CAPTURE CROSS SECTIONS OF HEAVY IONS  
from EXPERIMENTAL DATA AND EMPIRICAL FORMULAE

$$SR \quad X = 1.1e-8 * q^0.5 * (1 - \exp(-2.44e-5 * E^2 * 2.6)) / (E^4.8 * Zt^1.8)$$

$$w/ \quad E' = 1000 * E / (Zt^1.25 * q^0.7)$$

$$BL \quad X = 3.14 * (5.3e-9)^2 * Zt^0.33 * q^2 * (vo/v)^6$$

$$HJH \quad X = 1e-28 * q^2.5 * Zt^0.67 * \text{beta}^{-7}$$

$$VSN \quad X = 4 * 3.14 * (5.3e-9)^2 * Zt^0.33 * q^3 * (vo/v)^6$$

P	q	Zt	Beta	E	Xexpt	ref.	E'	X-SR	X-BL	X-HJH	X-VSN
				MeV/A							
C	5	2	0.067	2.098	8.4E-20	A	285.	1.1E-20 ***	4.8E-21	1.5E-18	9.7E-20
C	6	1	0.025	0.31	6.2E-17	F	88.4	1.1E-17 ***	1.7E-18	1.2E-15	4.2E-17
C	6	1	0.049	1.14	1.7E-19	F	325.	2.4E-20 ***	3.4E-20	1.2E-17	8.3E-19
C	6	2	0.025	0.31	1.3E-16	F	37.1	5.7E-17	2.2E-18	1.9E-15	5.3E-17
C	6	2	0.049	1.14	1.0E-18	F	136.	4.3E-19	4.3E-20	2.0E-17	1.0E-18
C	6	10	0.049	1.14	1.7E-17	F	18.2	1.7E-17	7.3E-20	5.7E-17	1.8E-18
C	6	18	0.049	1.14	3.3E-17	F	8.77	3.0E-17	8.8E-20	8.5E-17	2.2E-18
N	7	2	0.062	1.796	2.5E-19	A	193.	8.9E-20 ***	1.5E-20	5.9E-18	4.3E-19
O	8	2	0.073	2.492	8.6E-20	A	244.	3.1E-20	7.3E-21	2.6E-18	2.4E-19
F	9	2	0.073	2.492	1.4E-19	A	225.	4.8E-20	9.2E-21	3.5E-18	3.4E-19
Ar	13	7	0.084	3.35	5.3E-18	E	48.8	4.2E-18	1.2E-20	7.3E-18	6.4E-19
Ar	14	7	0.084	3.35	6.3E-18	E	46.3	5.1E-18	1.4E-20	8.8E-18	8.0E-19
Ar	15	7	0.084	3.35	1.2E-17	E	44.1	6.0E-18	1.6E-20	1.0E-17	9.9E-19
Ar	16	7	0.084	3.35	1.5E-17	E	42.2	7.0E-18	1.8E-20	1.2E-17	1.2E-18
Ar	17	7	0.084	3.35	1.4E-17	E	40.4	8.1E-18	2.1E-20	1.4E-17	1.4E-18
Ar	18	7	0.084	3.35	1.7E-17	E	38.9	9.3E-18	2.3E-20	1.6E-17	1.7E-18
Ar	13	7	0.111	5.8	8.0E-19	E	84.5	6.2E-19	2.4E-21	1.1E-18	1.3E-19
Ar	14	7	0.111	5.8	1.5E-18	E	80.3	7.9E-19	2.7E-21	1.3E-18	1.6E-19
Ar	15	7	0.111	5.8	1.6E-18	E	76.5	1.0E-18	3.1E-21	1.5E-18	1.9E-19
Ar	16	7	0.111	5.8	3.0E-18	E	73.1	1.2E-18	3.6E-21	1.8E-18	2.3E-19
Ar	17	7	0.111	5.8	3.3E-18	E	70.1	1.5E-18	4.0E-21	2.1E-18	2.8E-19
Ar	18	7	0.111	5.8	4.8E-18	E	67.3	1.8E-18	4.5E-21	2.4E-18	3.3E-19
Ar	13	7	0.123	7.1	4.6E-19	E	103.	2.5E-19	1.3E-21	5.3E-19	6.8E-20
Ar	15	7	0.123	7.1	1.1E-18	E	93.6	4.2E-19	1.7E-21	7.5E-19	1.0E-19
Ar	14	7	0.134	8.5	2.3E-19	E	117.	1.4E-19	8.8E-22	3.5E-19	5.0E-20
Ar	15	7	0.134	8.5	4.8E-19	E	112.	1.8E-19	1.0E-21	4.1E-19	6.2E-20
Ar	16	7	0.134	8.5	5.4E-19	E	107.	2.4E-19	1.2E-21	4.9E-19	7.5E-20
Ar	17	7	0.134	8.5	8.0E-19	E	102.	3.0E-19	1.3E-21	5.7E-19	9.0E-20
Ar	18	7	0.134	8.5	1.0E-18	B	98.7	3.7E-19	1.5E-21	6.5E-19	1.1E-19
Ar	16	18	0.084	3.4	2.3E-17	F	13.1	2.0E-17	2.5E-20	2.3E-17	1.6E-18
Ar	17	18	0.134	8.5	2.4E-18	F	31.5	2.8E-18	1.8E-21	1.1E-18	1.2E-19
Ar	18	18	0.134	8.5	2.4E-18	F	30.3	3.2E-18	2.0E-21	1.2E-18	1.5E-19
Fe	17	7	0.134	8.5	9.1E-19	E	102.	3.0E-19	1.3E-21	5.7E-19	9.0E-20
Fe	20	7	0.134	8.5	1.1E-18	E	91.6	5.4E-19	1.8E-21	8.5E-19	1.5E-19
Fe	23	7	0.134	8.5	2.3E-18	E	83.1	8.8E-19	2.4E-21	1.2E-18	2.2E-19
Fe	25	7	0.134	8.5	2.7E-18	E	78.4	1.2E-18	2.8E-21	1.5E-18	2.9E-19
Fe	26	7	0.134	8.5	3.4E-18	E	76.3	1.3E-18	3.0E-21	1.6E-18	3.2E-19
Fe	20	18	0.047	1.07	1.5E-16	F	3.54	4.1E-16	1.2E-18	2.2E-15	9.7E-17
Fe	21	18	0.047	1.07	1.4E-16	F	3.42	4.5E-16	1.3E-18	2.5E-15	1.1E-16
Fe	23	18	0.085	3.4	3.9E-17	F	10.2	4.2E-17	4.9E-20	5.4E-17	4.6E-18
Fe	24	18	0.085	3.4	4.3E-17	F	9.91	4.6E-17	5.4E-20	6.0E-17	5.3E-18
Fe	25	18	0.085	3.4	4.5E-17	F	9.63	5.0E-17	5.8E-20	6.6E-17	5.9E-18
Fe	25	18	0.134	8.4	5.7E-18	F	23.8	6.6E-18	3.0E-21	2.8E-18	3.9E-19
Fe	26	18	0.134	8.4	6.0E-18	F	23.1	7.2E-18	4.2E-21	3.1E-18	4.4E-19
Kr	21	7	0.134	8.5	4.5E-19	F	88.6	6.4E-19	2.0E-21	9.6E-19	1.7E-19
Kr	27	7	0.134	8.5	2.2E-18	E	74.3	1.5E-18	3.3E-21	1.8E-18	3.6E-19
Kr	33	7	0.134	8.5	6.6E-18	E	64.5	2.8E-18	4.9E-21	3.0E-18	6.6E-19
Nb	28	1	0.085	3.4	1.0E-19	F	329.	4.7E-20	2.8E-20	1.3E-17	3.2E-18
Nb	31	1	0.085	3.4	1.2E-19	F	307.	7.0E-20	3.4E-20	1.6E-17	4.4E-18
Nb	34	1	0.085	3.4	2.1E-19	F	288.	1.0E-19	4.1E-20	2.1E-17	5.8E-18
Nb	31	18	0.085	3.4	6.0E-17	F	8.28	7.8E-17	8.9E-20	1.1E-16	1.1E-17
Xe	34	7	0.134	8.5	3.7E-18	E	63.2	3.0E-18	5.2E-21	3.2E-18	7.2E-19
Xe	41	7	0.134	8.5	7.7E-18	E	55.4	5.1E-18	7.6E-21	5.1E-18	1.3E-18
Xe	46	7	0.134	8.5	1.2E-17	E	51.1	6.9E-18	9.5E-21	6.8E-18	1.8E-18
Xe	32	7	0.134	8.5	4.5E-18	C	65.9	2.5E-18	4.6E-21	2.8E-18	6.0E-19

TABLE II (contd.)

P	q	Zt	Beta	E	Xexpt	ref.	E'	X-SR	X-BL	X-HJH	X-VSN
				MeV/R							
Pb	51	1	0.099	4.66	3.1E-19	F	297.	1.1E-19	3.7E-20	1.9E-17	7.6E-18
Pb	52	1	0.099	4.66	3.2E-19	F	293.	1.1E-19	3.8E-20	2.0E-17	8.1E-18
Pb	53	1	0.099	4.66	3.3E-19	F	289.	1.2E-19	3.9E-20	2.1E-17	8.5E-18
Pb	54	1	0.099	4.66	3.8E-19	F	285.	1.3E-19	4.1E-20	2.2E-17	9.0E-18
Pb	55	1	0.099	4.66	3.9E-19	F	281.	1.4E-19	4.2E-20	2.3E-17	9.5E-18
Pb	56	1	0.099	4.66	4.6E-19	F	278.	1.5E-19	4.4E-20	2.4E-17	1.0E-17
Pb	57	1	0.099	4.66	4.8E-19	F	274.	1.6E-19	4.6E-20	2.5E-17	1.1E-17
Pb	58	1	0.099	4.66	4.4E-19	F	271.	1.7E-19	4.7E-20	2.6E-17	1.1E-17
Pb	59	1	0.099	4.66	4.6E-19	F	268.	1.9E-19	4.9E-20	2.7E-17	1.2E-17
Pb	54	2	0.099	4.66	8.9E-19	F	120.	2.4E-18 ***	5.1E-20	3.5E-17	1.1E-17
Pb	37	7	0.099	4.66	3.0E-17	C	32.6	2.1E-17	3.7E-20	3.2E-17	5.5E-18
Pb	40	7	0.099	4.66	4.0E-17	C	30.9	2.5E-17	4.3E-20	3.8E-17	7.0E-18
Pb	52	7	0.099	4.66	9.0E-17	C	25.7	4.3E-17	7.2E-20	7.4E-17	1.5E-17
Pb	37	7	0.134	8.5	6.5E-18	C	59.6	3.9E-18	6.2E-21	4.0E-18	9.3E-19
Pb	40	7	0.134	8.5	7.0E-18	C	56.4	4.8E-18	7.2E-21	4.8E-18	1.2E-18
Pb	52	7	0.134	8.5	1.0E-17	C	46.9	9.4E-18	1.2E-20	9.3E-18	2.6E-18
Pb	40	7	0.112	5.9	1.3E-17	D	39.1	1.4E-17	2.1E-20	1.7E-17	3.5E-18
Pb	54	7	0.099	4.66	8.8E-17	F	25.0	4.7E-17	7.8E-20	8.1E-17	1.7E-17
Pb	55	7	0.112	5.9	2.2E-17	D	31.3	2.8E-17	4.0E-20	3.7E-17	9.0E-18
Pb	54	10	0.099	4.66	4.8E-17	F	16.0	6.8E-17	8.7E-20	1.0E-16	1.9E-17
Pb	54	18	0.099	4.66	8.3E-17	F	7.70	1.2E-16	1.1E-19	1.5E-16	2.3E-17
Pb	54	54	0.099	4.66	7.5E-17	F	1.95	3.5E-16 ***	1.5E-19	3.2E-16	3.4E-17
U	14	1	0.054	1.4	6.0E-19	D	220.	2.3E-19	1.0E-19	5.0E-17	5.7E-18
U	20	1	0.054	1.4	1.0E-18	D	171.	9.2E-19	2.0E-19	1.2E-16	1.7E-17
U	30	1	0.054	1.4	4.0E-18	D	129.	4.4E-18	4.6E-19	3.4E-16	5.6E-17
U	40	1	0.128	7.8	1.2E-18	D	589.	3.5E-21 ***	4.8E-21	1.7E-18	7.9E-19
U	63	1	0.145	10	3.6E-19	D	550.	6.1E-21 ***	5.8E-21	2.3E-18	1.5E-18
U	10	7	0.054	1.4	1.0E-18	D	24.5	2.1E-17 ***	9.7E-20	7.9E-17	4.0E-18
U	20	7	0.054	1.4	2.0E-17	D	15.1	9.1E-17 ***	3.9E-19	4.5E-16	3.2E-17
U	30	7	0.054	1.4	1.2E-16	D	11.3	2.1E-16	8.7E-19	1.2E-15	1.1E-16
U	63	7	0.145	10	1.6E-17	D	48.3	9.6E-18	1.1E-20	8.5E-18	2.8E-18

\*\*\* more than a factor of two difference between X-expt and X-SR

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TABLE III

COMPARISON OF ELECTRON LOSS CROSS SECTIONS OF HEAVY IONS  
from EXPERIMENTAL WORKS and EMPIRICAL FORMULAE

$$\begin{aligned} BL \quad X &= 3.14 * (5.3e-9)^2 * Zt^0.67 * Zp^1.33 * q^{-3} * (vo/v)^2 \\ HCH \quad X &= 9e-19 * q^{-3} * beta^{-1} * Zt * Zp^2 \\ JA \quad X &= 1e-19 * q^{-3} * beta^{-1.5} * Zp^2 * Zt \\ JA1 \quad X &= 5e-19 * q^{-2} * beta^{-1} * Zp^1.33 * Zt \end{aligned}$$

P	Zp	q	Zt	Beta	E	X-expt	Ref.	X-HCH		X-JA		X-JA1		X-BL	
								MeV/A							
Ar	18	13	7	0.0845	3.35	8.6E-18	E	1.1E-17		4.2E-18	1.1E-17	5.2E-18			
Ar	18	14	7	0.0845	3.35	4.3E-18	E	8.8E-18		3.4E-18	9.9E-18	4.1E-18			
Ar	18	15	7	0.0845	3.35	2.3E-18	E	7.2E-18 ***		2.7E-18	8.6E-18	3.4E-18			
Ar	18	13	7	0.111	5.8	6.6E-18	E	8.4E-18		2.8E-18	8.7E-18	3.0E-18			
Ar	18	14	7	0.111	5.8	4.6E-18	E	6.7E-18		2.2E-18	7.5E-18	2.4E-18			
Ar	18	15	7	0.111	5.8	2.2E-18	E	5.4E-18		1.8E-18	6.5E-18	1.9E-18			
Ar	18	13	7	0.123	7.1	5.7E-18	E	7.6E-18		2.4E-18	7.9E-18	2.4E-18			
Ar	18	15	7	0.123	7.1	2.3E-18	E	4.9E-18		1.6E-18	5.9E-18	1.6E-18			
Ar	18	13	7	0.134	8.5	5.2E-18	E	6.9E-18		2.1E-18	7.2E-18	2.1E-18			
Ar	18	14	7	0.134	8.5	3.1E-18	E	5.6E-18		1.7E-18	6.2E-18	1.6E-18			
Ar	18	15	7	0.134	8.5	1.8E-18	E	4.5E-18 ***		1.4E-18	5.4E-18	1.3E-18			
Ar	18	16	7	0.134	8.5	4.3E-18	E	3.7E-18		1.1E-18	4.8E-18	1.1E-18			
Ar	18	17	7	0.134	8.5	3.7E-18	E	3.1E-18		9.4E-19	4.2E-18	9.2E-19			
Ar	18	17	18	0.134	8.5	2.5E-18	F	8.0E-18 ***		2.4E-18	1.1E-17	1.7E-18			
Fe	26	17	7	0.134	8.5	8.2E-18	E	6.5E-18		2.0E-18	6.9E-18	1.5E-18			
Fe	26	20	7	0.134	8.5	4.1E-18	E	4.0E-18		1.2E-18	5.0E-18	9.2E-19			
Fe	26	23	7	0.134	8.5	8.0E-19	E	2.6E-18 ***		7.9E-19	3.8E-18	6.0E-19			
Fe	26	25	7	0.134	8.5	3.2E-19	E	2.0E-18 ***		6.2E-19	3.2E-18	4.7E-19			
Kr	36	21	7	0.134	8.5	9.4E-18	E	6.6E-18		2.0E-18	7.0E-18	1.2E-18			
Kr	36	27	7	0.134	8.5	1.8E-18	E	3.1E-18		9.4E-19	4.2E-18	5.8E-19			
Kr	36	33	7	0.134	8.5	2.3E-19	E	1.7E-18 ***		5.1E-19	2.8E-18	3.2E-19			
Nb	41	28	1	0.0852	3.4	3.2E-19	F	8.1E-19 ***		3.1E-19	1.0E-18	4.1E-19			
Nb	41	31	1	0.0852	3.4	2.2E-19	F	6.0E-19		2.3E-19	8.5E-19	3.0E-19			
Nb	41	34	1	0.0852	3.4	4.0E-20	F	4.5E-19 ***		1.7E-19	7.1E-19	2.3E-19			
Nb	41	31	18	0.0852	3.4	1.2E-18	F	1.1E-17 ***		4.1E-18	1.5E-17	2.1E-18			
Xe	54	20	1	0.447	110	9.0E-19	G	7.3E-19		1.2E-19	5.6E-19	5.9E-20			
Xe	54	30	1	0.447	110	4.0E-19	G	2.2E-19		3.6E-20	2.5E-19	1.8E-20			
Xe	54	40	1	0.447	110	1.5E-19	G	9.2E-20		1.5E-20	1.4E-19	7.4E-21			
Xe	54	10	7	0.447	110	2.2E-17	G	4.1E-17		6.8E-18	1.6E-17	1.7E-18			
Xe	54	20	7	0.447	110	1.2E-17	G	5.1E-18		8.5E-19	3.9E-18	2.2E-19			
Xe	54	30	7	0.447	110	6.0E-18	G	1.5E-18		2.5E-19	1.8E-18	6.5E-20			
Xe	54	40	7	0.447	110	2.0E-18	G	6.4E-19		1.1E-19	9.9E-19	2.7E-20			
Xe	54	28	7	0.134	8.5	1.8E-17	E	6.2E-18		1.9E-18	6.7E-18	8.8E-19			
Xe	54	34	7	0.134	8.5	5.3E-18	E	3.5E-18		1.1E-18	4.6E-18	4.9E-19			
Xe	54	41	7	0.134	8.5	1.6E-18	E	2.0E-18		6.0E-19	3.1E-18	2.8E-19			
Xe	54	32	7	0.134	8.5	4.5E-18	C	4.2E-18		1.3E-18	5.1E-18	5.9E-19			
Hg	80	10	7	0.447	110	1.7E-17	G	9.0E-17 ***		1.5E-17	2.7E-17	2.9E-18			
Hg	80	20	7	0.447	110	9.2E-18	G	1.1E-17		1.9E-18	6.6E-18	3.7E-19			
Hg	80	34	7	0.447	110	5.6E-18	G	2.3E-18		3.8E-19	2.3E-18	7.5E-20			
Hg	80	52	7	0.447	110	1.5E-18	G	6.4E-19		1.1E-19	9.8E-19	2.1E-20			
Pb	82	51	1	0.0996	4.66	4.3E-19	F	4.6E-19		1.6E-19	6.8E-19	1.3E-19			
Pb	82	52	1	0.0996	4.66	3.5E-19	F	4.3E-19		1.5E-19	6.5E-19	1.2E-19			
Pb	82	53	1	0.0996	4.66	3.4E-19	F	4.1E-19		1.4E-19	6.3E-19	1.1E-19			
Pb	82	54	1	0.0996	4.66	2.5E-19	F	3.9E-19		1.4E-19	6.0E-19	1.1E-19			
Pb	82	55	1	0.0996	4.66	2.3E-19	F	3.7E-19		1.3E-19	5.8E-19	1.0E-19			
Pb	82	56	1	0.0996	4.66	2.1E-19	F	3.5E-19		1.2E-19	5.6E-19	9.5E-20			
Pb	82	57	1	0.0996	4.66	1.8E-19	F	3.3E-19		1.2E-19	5.4E-19	9.0E-20			
Pb	82	58	1	0.0996	4.66	1.4E-19	F	3.1E-19		1.1E-19	5.2E-19	8.5E-20			
Pb	82	59	1	0.0996	4.66	1.4E-19	F	3.0E-19		1.0E-19	5.1E-19	8.1E-20			
Pb	82	54	2	0.0996	4.66	2.8E-19	F	7.7E-19 ***		2.7E-19	1.2E-18	1.7E-19			
Pb	82	37	7	0.0996	4.66	2.0E-17	C	8.4E-18		3.0E-18	9.0E-18	1.2E-18			
Pb	82	40	7	0.0996	4.66	1.5E-17	C	6.6E-18		2.3E-18	7.7E-18	9.6E-19			
Pb	82	52	7	0.0996	4.66	3.0E-18	C	3.0E-18		1.1E-18	4.6E-18	4.4E-19			
Pb	82	37	7	0.134	8.5	1.0E-17	C	6.2E-18		1.9E-18	6.7E-18	6.7E-19			
Pb	82	40	7	0.134	8.5	1.0E-17	C	4.9E-18		1.5E-18	5.7E-18	5.3E-19			
Pb	82	40	7	0.112	5.9	1.6E-17	D	5.9E-18		2.0E-18	6.9E-18	7.6E-19			
Pb	82	52	7	0.134	8.5	3.0E-18	C	2.2E-18		6.8E-19	3.4E-18	2.4E-19			
Pb	82	54	7	0.0996	4.66	3.2E-18	F	2.7E-18		9.5E-19	4.2E-18	3.9E-19			
Pb	82	55	7	0.112	5.9	6.6E-18	D	2.3E-18		7.5E-19	3.6E-18	2.9E-19			
Pb	82	54	10	0.0996	4.66	1.8E-18	F	3.9E-18		1.4E-18	6.0E-18	4.9E-19			
Pb	82	54	18	0.0996	4.66	2.5E-18	F	6.9E-18 ***		2.4E-18	1.1E-17	7.3E-19			
Pb	82	54	54	0.0996	4.66	3.9E-18	F	2.1E-17 ***		7.3E-18	3.3E-17	1.5E-18			

TABLE III(conti.)

P	Zp	q	Zt	Beta	E MeV/A	X-expt	Ref.	X-HCH	X-JA	X-JA1	X-BL
U	92	10	1	0.0547	1.4	3.0E-17	D	1.4E-16 ***	6.6E-17	3.7E-17	6.4E-17
U	92	14	1	0.0547	1.4	1.3E-17	D	5.1E-17 ***	2.4E-17	1.9E-17	2.3E-17
U	92	20	1	0.0547	1.4	7.0E-18	D	1.7E-17 ***	8.3E-18	9.3E-18	8.0E-18
U	92	30	1	0.0547	1.4	1.3E-18	D	5.2E-18 ***	2.5E-18	4.2E-18	2.4E-18
U	92	40	1	0.1286	7.8	1.0E-19	D	9.3E-19 ***	2.9E-19	9.9E-19	1.8E-19
U	92	63	1	0.0547	10	1.6E-19	D	5.6E-19 ***	2.6E-19	9.4E-19	2.6E-19
U	92	10	7	0.0547	1.4	4.0E-16	D	9.7E-16	4.6E-16	2.6E-16	2.4E-16
U	92	20	7	0.0547	1.4	4.0E-17	D	1.2E-16 ***	5.8E-17	6.5E-17	3.0E-17
U	92	30	7	0.0547	1.4	1.2E-17	D	3.6E-17 ***	1.7E-17	2.9E-17	8.8E-18
U	92	30	7	0.0547	1.4	3.0E-17	D	3.6E-17	1.7E-17	2.9E-17	8.8E-18
U	92	63	7	0.1453	10	8.0E-18	D	1.5E-18	4.3E-19	2.5E-18	1.3E-19
U	92	40	18	0.0547	1.4	8.0E-18	D	3.9E-17 ***	1.9E-17	4.2E-17	7.0E-18
U	92	50	18	0.0547	1.4	1.3E-18	D	2.0E-17 ***	9.5E-18	2.7E-17	3.6E-18
U	92	10	1	0.447	110	3.0E-18	G	1.7E-17 ***	2.8E-18	4.6E-18	9.6E-19
U	92	20	1	0.447	110	1.5E-18	G	2.1E-18	3.5E-19	1.1E-18	1.2E-19
U	92	30	1	0.447	110	1.0E-18	G	6.3E-19	1.0E-19	5.1E-19	3.6E-20
U	92	40	1	0.447	110	6.5E-19	G	2.7E-19	4.4E-20	2.9E-19	1.5E-20
U	92	50	1	0.447	110	4.5E-19	G	1.4E-19	2.3E-20	1.8E-19	7.7E-21
U	92	10	7	0.447	110	4.0E-17	G	1.2E-16 ***	2.0E-17	3.2E-17	3.5E-18
U	92	20	7	0.447	110	2.5E-17	G	1.5E-17	2.5E-18	8.0E-18	4.4E-19
U	92	30	7	0.447	110	1.7E-17	G	4.4E-18	7.3E-19	3.6E-18	1.3E-19
U	92	40	7	0.447	110	1.1E-17	G	1.9E-18 ***	3.1E-19	2.0E-18	5.5E-20
U	92	50	7	0.447	110	7.0E-18	G	9.5E-19 ***	1.6E-19	1.3E-18	2.8E-20

## References for experimental data:

- A = T.R. Dillingham, et. al., Phys. Rev. A24, 1237 (1981).  
 B = H. Gould, et. al., Phys. Rev. Lett, 41, 1457 (1978).  
 C = J. Alonso and H. Gould, Phys. Rev. A26, 1134 (1982).  
 D = B. Franzke, IEEE Trans. Nucl. Sci. NS-28, 2116 (1981).  
 E = J. Alonso, et. al., IEEE Trans. Nucl. Sci. NS-26, 3686 (1979).  
 F = W.G. Graham, et. al., Phys. Rev. A30, 722 (1984).  
 G = Calculations by G.H. Gillespie using "Sum Rules"  
     G.H. Gillespie, et. al., Proc. Heavy Ion Fusion Workshop, 1977 & 1978.  
     and Phys. Rev. A17, 1284 (1978).

\*\*\* more than a factor of two difference between X-expt and X-HCH

X-HCH = best fitting based on the following three references.

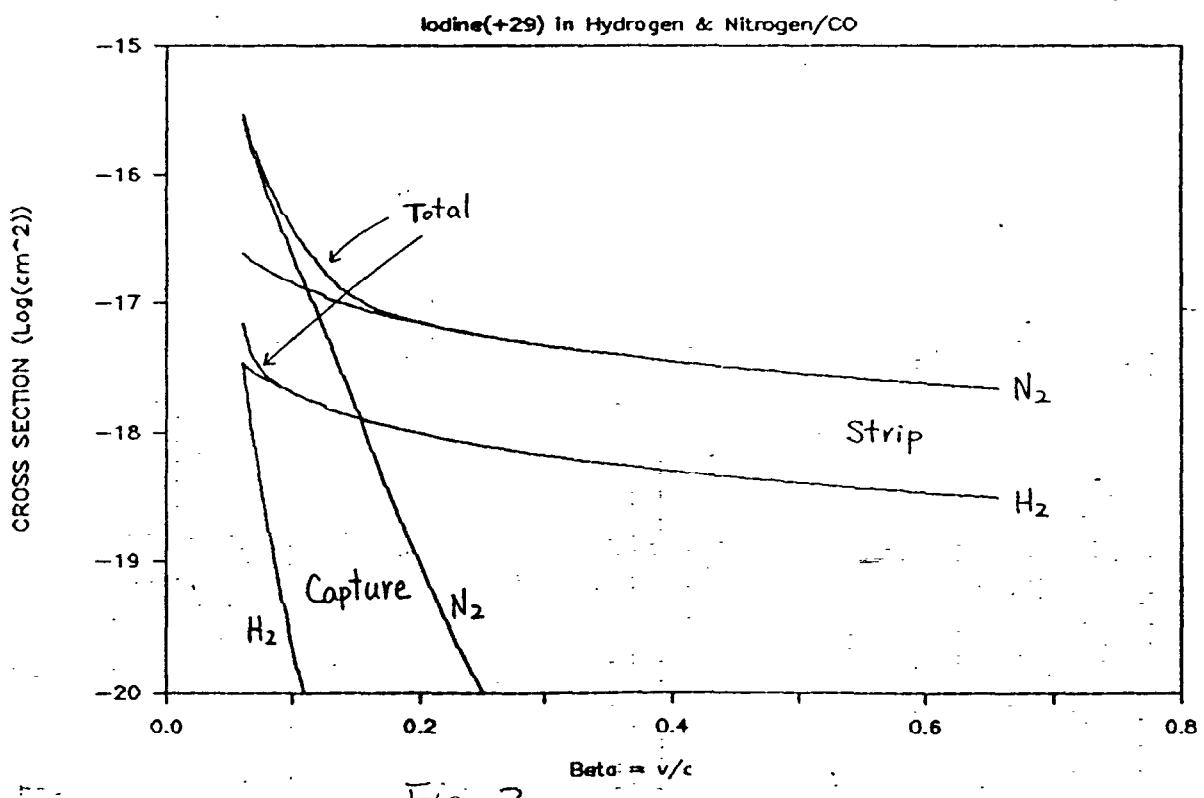
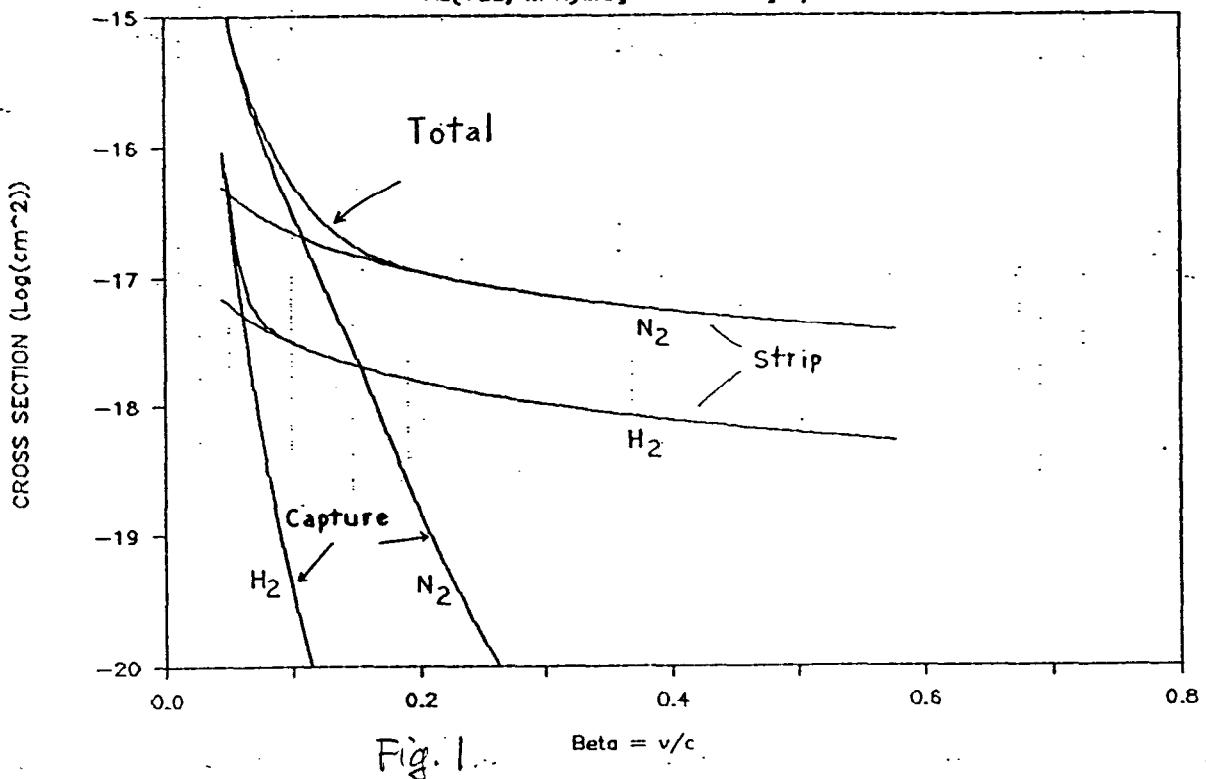
X-BL = N. Bohr & J. Lindhard, K. Dan Vidensk. Mat. Fys. Medd. 28, 7 (1954).  
 or H.D. Betz, Rev. Mod. Phys. 44, 465(1972).

X-JA = J. Alonso &amp; H. Gould, Phys. Rev. A26, 1134(1982).

X-JA1 = Modification to X-JA.

## CHARGE EXCHANGE CROSS SECTIONS

*Au(+33) in Hydrogen and Nitrogen/CO*



## BEAM LOSS DUE TO CHARGE EXCHANGE

*Au(+33, 0.92 MeV/amu from Tvdg)*

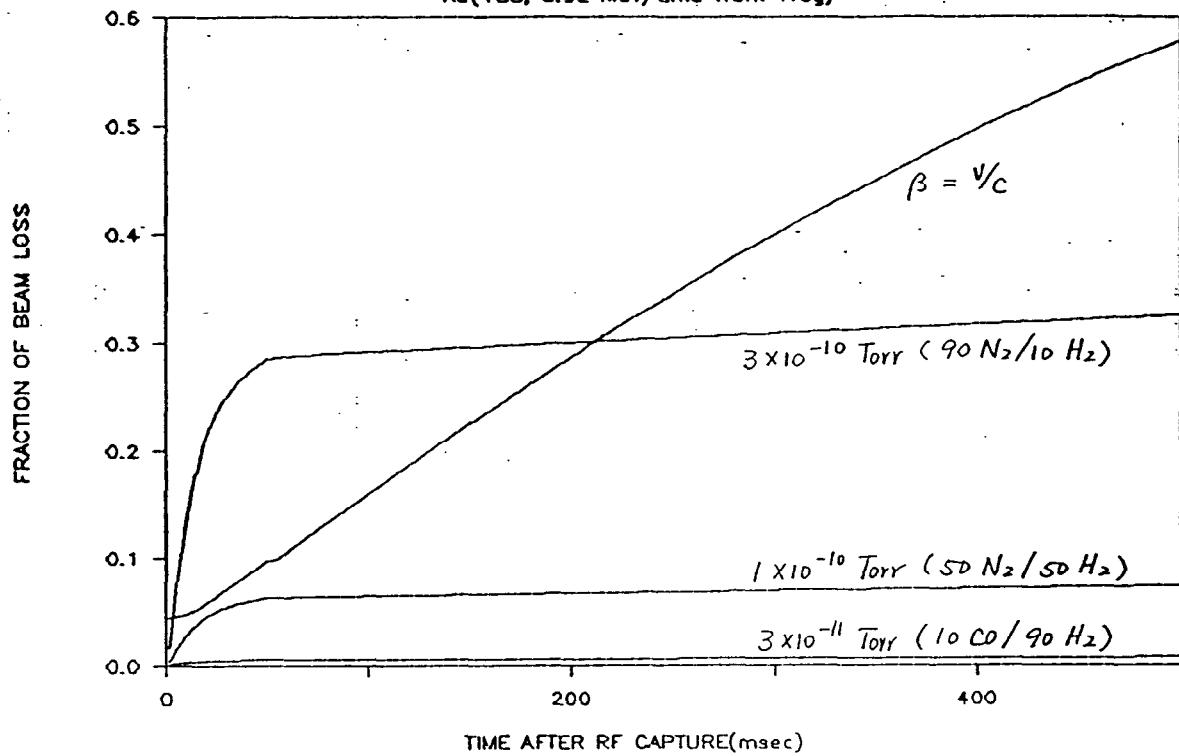


Fig. 3.

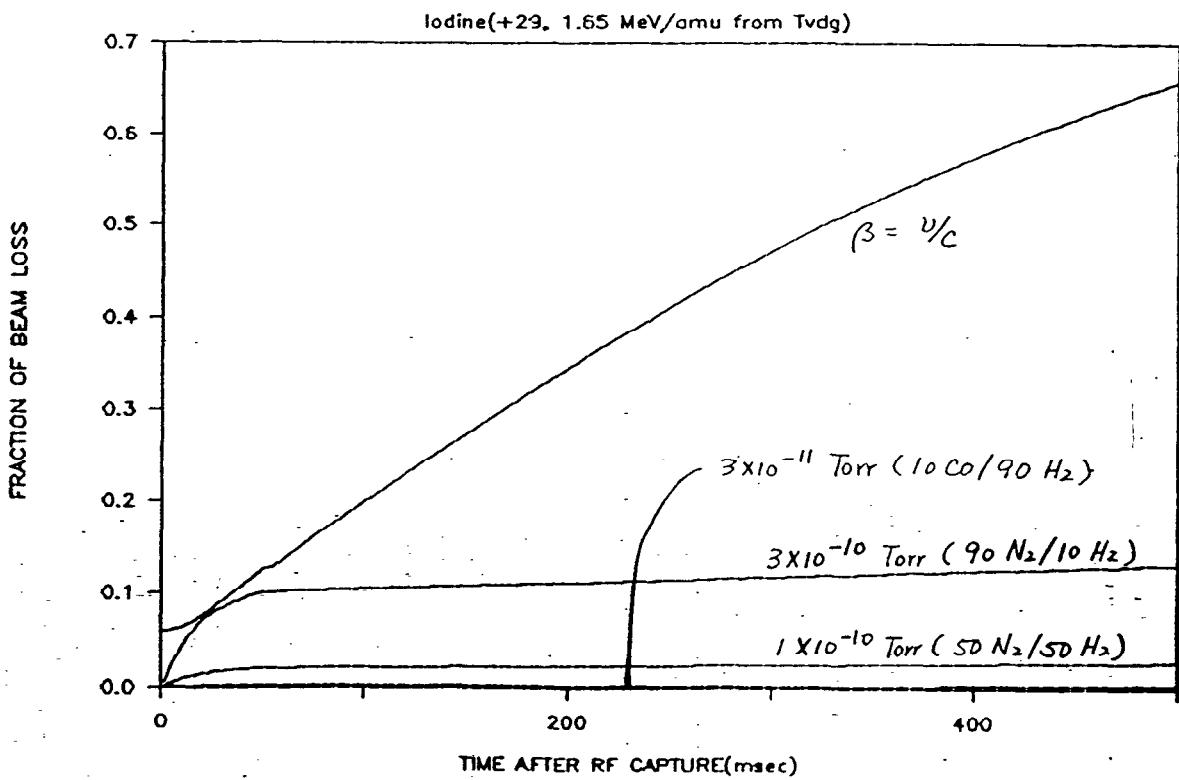


Fig 4.